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Development of the loss coefficient correlation for cross flow between graphite fuel blocks in the core of prismatic very high temperature reactor-PMR200

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HIGHLIGHTS

- Cross flow experimental data are produced with wedge-shaped and parallel gaps.
- The results of a CFD analysis and experimental data are in good agreement.
- Pressure loss coefficient for the cross gap between fuel blocks in PMR200 is found.
- A new correlation of the cross flow loss coefficient for PMR200 is proposed.

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ABSTRACT

The core of the very high temperature reactor (VHTR) PMR200 (a prismatic modular reactor rated at 200 MW of thermal power) consists of hexagonal prismatic fuel blocks and reflector blocks made of graphite. If the core bypass flow ratio increases, the coolant channel flow is decreased and can then lower the heat removal efficiency, resulting in a locally increased fuel block temperature. The coolant channels in the fuel blocks are connected to bypass gaps by the cross gap, complicating flow distribution in the VHTR core. Therefore, reliable estimation of the bypass flow is highly important for the design and safety analysis of the VHTR core. Because of the complexity of the core geometry and gap configuration, it is challenging to predict the flow distribution in the VHTR core. To analyze this flow distribution accurately, it is necessary to determine the cross flow phenomena, and the loss coefficient across the cross gap has to be evaluated to determine the flow distribution in the VHTR core when a lumped parameter code or a flow network analysis code that uses the correlation of the loss coefficient is employed. The purpose of this paper is to develop a loss coefficient correlation applicable to the cross gap in the PMR200 core. The cross flow was evaluated experimentally using the difference between the measured inlet and outlet mass flow rates. Next, the applicability of a commercial computational fluid dynamics (CFD) code, CFX 15, was confirmed by comparing the experimental data and CFD analysis results. To understand the cross flow phenomena, the loss coefficient was evaluated; in the high Reynolds number region, the cross flow loss coefficient on Reynolds number is nearly constant regardless of the Reynolds number, whereas it varies with the gap size in the low Reynolds number region. Finally, the loss coefficient correlation was proposed on the basis of experiments and the CFD analysis. The developed correlation was compared with existing correlations, and the developed one shows better agreement with the experimental results than the existing ones. Hence, the developed correlation will be applied to the flow network code to analyze flow distribution in the PMR200 core.

1. Introduction

The very high temperature reactor (VHTR) is a helium-gas-cooled and graphite-moderated reactor. It was chosen as one of the Generation IV reactors owing to its advantages, e.g., enhanced fuel integrity, proliferation resistance, relatively simple fuel cycle, and modularity to supply electricity (Gauthier et al., 2006). The

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Nomenclature

A_{CH}	coolant channel area
A_{CG}	inlet cross-sectional area of the crossflow gap
A_{BG}	bypass gap area
a	length of one edge of the hexagonal interface at the cross gap
C_1, C_2	empirically determined constant values for equation fitting
CR	ratio of mass flow rate at the cross gap to that at the outlet of the downstream block
D	channel diameter
D_H	hydraulic diameter of the pipe
D_{CH}	channel diameter at the coolant hole
D_{BGh}	hydraulic diameter at the bypass gap
Eu	Euler number
f	friction factor through the flow channel
g	local acceleration due to gravity
K	pressure loss coefficient
K_{Gr}	Groehn's pressure loss coefficient
K_{Ka}	Kaburaki's pressure loss coefficient
L	length of the flow channel
m_{cross}	mass flow rate at the cross gap
m_{main}	mass flow rate at the outlet of the downstream block
P	wetted perimeter
P_{wedge}	wetted perimeter for the wedge-shaped gap
$P_{parallel}$	wetted perimeter for the parallel gap
Q_{jn}	flow rate of n-th flow path at node j
Q_{kn}	flow rate of n-th flow path at the k-th loop
R_{CH}	flow resistance at the coolant hole
R_{BG}	flow resistance at the bypass gap
R_{CG}	flow resistance at the cross gap
Re	Reynolds number
Re_{CG}	Reynolds number at the cross gap opening
v	velocity of air
ΔP	pressure difference
δ	gap width
μ	dynamic viscosity
ρ	density of air
$\emptyset$	solution extrapolated by Richardson extrapolation method

prismatic modular reactor (PMR) is one prospective VHTR candidate, and the graphite block of the PMR reportedly offers advantages for neutron economy and high-temperature structural integrity (Baxter et al., 2000). Because the core of the prismatic VHTR consists of hexagonal graphite blocks, as shown in Fig. 1(a), there are gaps between the core elements to enable installation and refueling processes. The flow that passes through the vertical gap is called the bypass flow, and the flow that passes through the horizontal gaps is called the cross flow, as illustrated in Fig. 1 (b). The shape of the graphite blocks changes during reactor operation because of neutron exposure and thermal expansion (General Atomics, 1988).

It was reported that during operation of the Fort St. Vrain reactor, fluctuations in the primary coolant outlet temperature and the reactor power were caused by the bypass flow and cross flow (Olson et al., 1982). Consequently, the importance of the bypass flow and cross flow has been identified, and several studies of these phenomena have been conducted. Groehn (1982) studied the effect of cross flow on the main coolant flow at a two-block test section with a wedge-shaped gap. Kaburaki and Takizuka (1990) experimentally and numerically studied the cross flow characteristics at a parallel gap and a wedge-shaped gap. Sato et al. (2010) investigated the cooling effect of bypass flow using a computational fluid dynamics (CFD) code and concluded that the maximum fuel temperature and maximum coolant outlet temperature are increased by an increased gap width in the bypass flow, further concluding that the bypass flow causes a large lateral temperature gradient in the block. Johnson and Sato (2012) conducted a CFD analysis of a one-twelfth symmetric sector during normal operation in a 350-MWth prismatic VHTR; this study showed that increasing the gap width increases the maximum fuel temperature while providing significant cooling to the near-gap region. Kim and Lim (2011) evaluated the local gap size variation between graphite blocks and analyzed the core bypass flow and hot spot based on the calculated gap distributions. Yoon et al. (2011, 2012) conducted an experimental study and CFD analysis of a multiblock facility with varying bypass gap size and cross gap size; the CFD model was validated using experimental data, and the effect of the bypass flow and cross flow on the flow distribution in a prismatic VHTR core was investigated. Tung et al. (2012) applied CFD analysis to investigate the effects of graphite surface roughness on the bypass flow in a high temperature gas-cooled reactor; the results indicated that increasing the surface roughness increases the maximum fuel and helium temperatures, as does increasing the gap width. Wang et al. (2014, 2015) conducted a CFD analysis and experimental study to investigate the coolant distribution in the reactor core on the basis of the two-layer block facility built at Texas A&M University. They provided a guideline and validating source for related experiments and provided experimental data as a benchmark for related numerical calculations.

Because of the random nature of gap creation, analysis of the core flow distribution in the VHTR requires a stochastic approach to possible combinations of gap configurations, rather than a deterministic approach. However, the large computational cost and time required to implement CFD codes simulating the entire core hinders their application to analysis of the gap effect. An alternative technique is the utilization of a flow network code, which uses a lumped parameter model and simulates a number of possible combinations of gap configurations that can be created in the VHTR's core (Vilim, 2007; Maruyama et al., 1988; Lee et al., 2012). The flow network code presents flow paths as a network of flow resistances, and thus requires the precise relation between the pressure loss and flow rate in a given geometry. In the VHTR core, there are three types of flow paths: coolant channel, bypass gap, and cross gap. These flow paths can be represented as a flow network, as shown in Fig. 2. The coolant channel is the normal pipe flow, and the bypass gap is the flow between parallel plates, which can be analyzed using equations that relate the head loss due to friction along a given length of channel to the average velocity of the fluid flow. However, the relation between the pressure loss and flow rate at the cross gap cannot be analyzed easily because of its complex geometry. Moreover, the cross gap complicates the flow distribution in the connecting flow path between the coolant channel and bypass gap. For these reasons, the cross flow in the VHTR core was studied experimentally to enhance the calculation accuracy of the flow network code using the correlation of the cross flow loss coefficient (Lee et al., 2012, 2015).

Therefore, the objectives of this study are to provide experimental data for the cross flow rate in the PMR200 core, to evaluate the pressure loss coefficients of the cross flow, and finally, to develop correlations for the cross flow loss coefficients for PMR200. For this purpose, an experimental facility with two stacked full-scale fuel blocks was constructed to reproduce the cross flow phenomena. Between the fuel blocks, two types of cross